SANS MEASUREMENTS OF NANOSCALE LITHOGRAPHIC FEATURES

The continued growth of the semiconductor industry depends on advances in lithographic processes and materials to enable the economical production of smaller device features. Precise measurement of the size and quality of lithographically prepared features is critical as their sizes continue to decrease, with dimensions approaching 100 nm. Current microscopy-based techniques such as scanning electron microscopy (SEM) and atomic force microscopy (AFM) often require special modifications to enable the measurement of either the critical dimensions or feature resolution parameters. More importantly, these techniques become extremely challenging as feature sizes continue to decrease.

In this highlight, we demonstrate the powerful use of small-angle neutron scattering (SANS) to quickly, non-destructively, and quantitatively characterize both the size and profile of lithographically prepared structures as prepared on a silicon wafer substrate [1]. Until recently, SANS instruments were unable to measure lithographic feature sizes (sizes greater than 300 nm) and neutron beam fluxes were insufficient to measure scattering from thin film structures. Today, with new focusing optics, the high intensity NCNR instruments allow routine SANS measurements of smaller lithographic features [2]. Other important advantages for the use of SANS to measure lithographic structures include a) the measurement of structures on silicon, because single crystal silicon wafers are generally transparent to neutrons, b) a measurement metric statistically averaged over an area of several square centimeters, and c) less stringent SANS instrument requirements as lithographic structures decrease in size.

As an example, periodic, equally spaced, parallel line patterns with a nominal size of 150 nm were prepared on a silicon single crystal wafer using standard 248 nm optical lithography, and placed directly in and normal to the neutron beam. Quantitative measurements of the size and average profile of these lines are extracted from the scattering data. SEM micrographs of these structures are shown in Fig. 1.

The SANS measurements were performed on the NG-7 30 m SANS line under ambient atmospheric conditions at the NCNR. Newly developed neutron focusing optics consisting of 28 biconcave MgF_2 lenses were used to access small enough angles to resolve feature sizes up to 300 nm, a previously inaccessible length scale for SANS. In this configuration, the SANS data provide quantitative information about the line repeat distance and the quality of the line structure.

The 2-D scattering data from the structures displayed in Fig. 1 are shown in Fig. 2. The line structures are aligned with the vertical

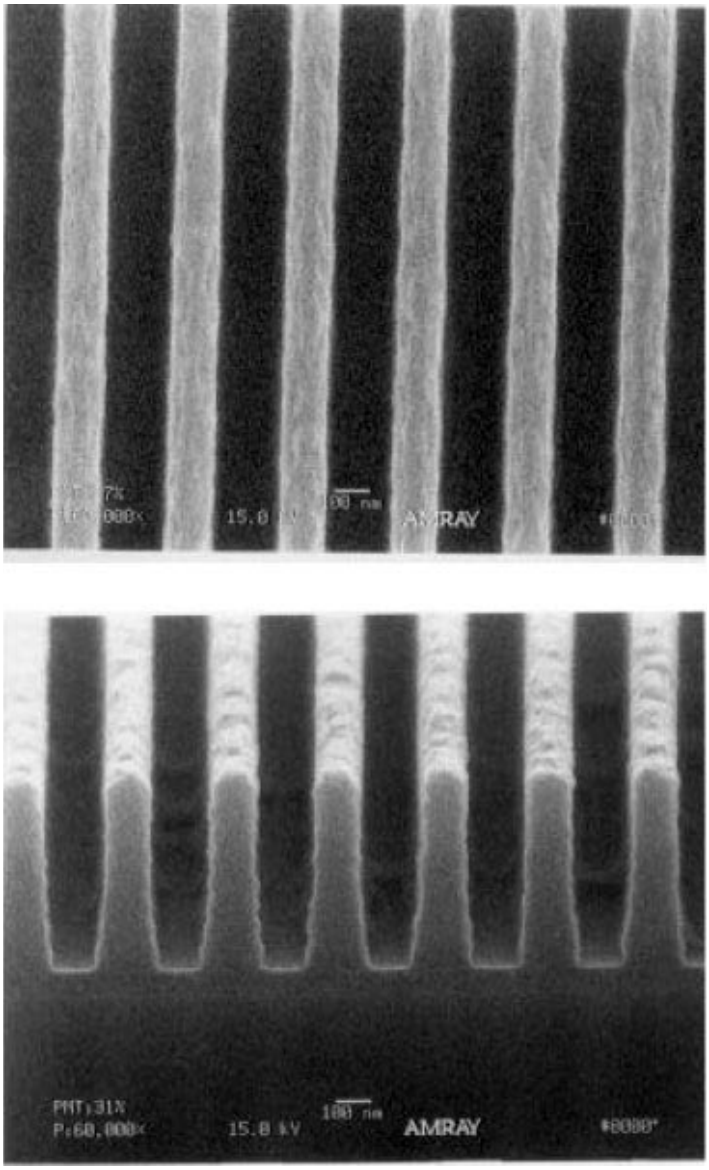

FIGURE 1. Top-down and side view scanning electron micrographs of the lithographically prepared lines used in the SANS measurement. The lines are nominally 150 nm wide and 0.62 μm in height.

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axis of the detector. Six orders of diffraction peaks are immediately observed in the horizontal axis of the detector because of the highly periodic pattern of the fabricated lines. By linearly fitting the peak position plotted as a function of the diffraction order index, the feature repeat distance for the structure in Fig. 1 is determined to be (3031 ± 9) Å.

A more detailed analysis provides a quantitative determination of the average profile of the line structures, including a measure of the line-edge roughness (LER). We model the periodic line pattern as a convolution of a periodic delta function with the average cross-section of a line. In Fig. 3, the scattering intensity of a given diffraction peak is plotted as a function of the position of the peak. The solid line is the best theoretical fit to the experimental data and corresponds to a measure of the LER of (213 ± 13) Å. Also in Fig. 3, the second and fourth order diffraction peaks are visible and less intense than the first and third diffraction peaks. The measurable intensity of the even order diffraction peaks indicates that the line feature size is slightly less than one half the overall repeat distance. The model fit results in a line feature size of (1350 ± 60) Å.

The average line structural size and cross-section were determined in a configuration where the sample was placed perpendicular to the incident neutron beam. More three-dimensional information about the average line structure can be obtained by tilting the line pattern with respect to the incident beam. Varying projections of the line profile onto the detector plane provide an elegant method to deduce more specific structural information. In additional, the formalism to extend the SANS theoretical framework to arbitrary shapes is well established and will be applied in the future. With these advances, SANS may be used to identify resolution limits in new nanofabrication processes and materials and to serve as an important metrology tool in understanding the physical processes that control the resolution of these methods.

REFERENCES

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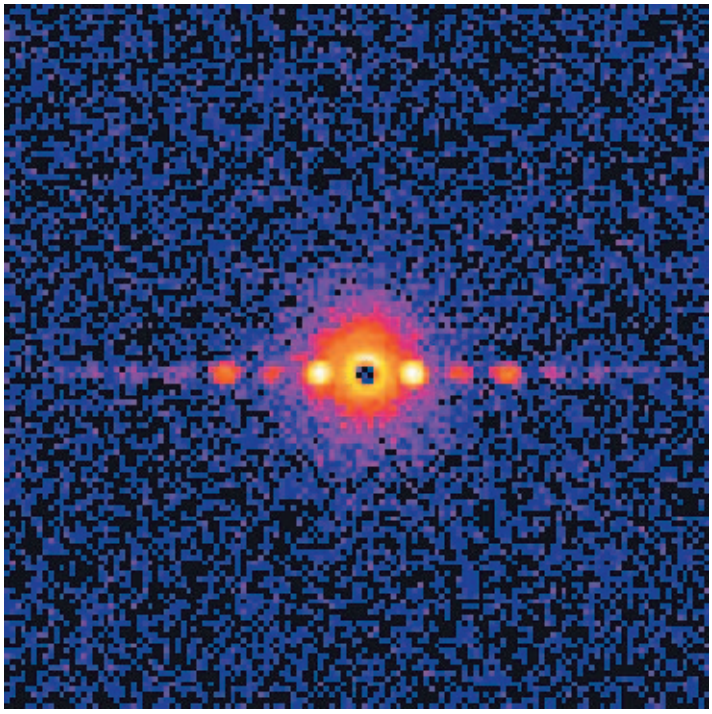

FIGURE 2. Two-dimensional SANS pattern from the sample shown in Fig. 1. Six orders of diffraction are observed due to the high resolution of the lithographically prepared pattern.

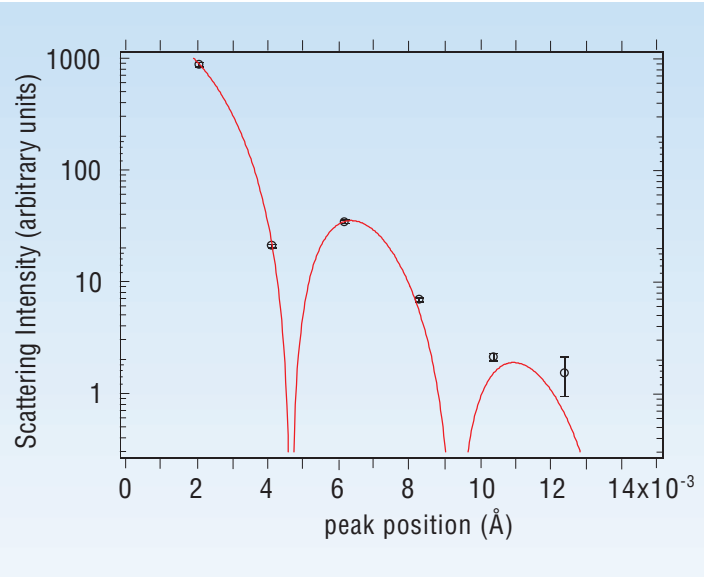

FIGURE 3. Scattering Intensity of each diffraction peak as a function of the peak position. The solid represents the best theoretical fit to the data.